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Magnetoresistive Properties of Tb/Ti and Tb/Si Multilayers

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Abstract. Magnetic, magnetoresistive and structural properties of Tb/Ti and Tb/Si nanoscale multilayers prepared by alternative deposition of Tb layers and Ti or Si spacers are comparatively studied. It was concluded that spin disorder scattering is responsible for the negative longitudinal magnetoresistance observed in multilayers of both types.

Introduction

Magnetic and magnetoresistive properties of FM/NM nanoscale multilayers and FM-NM granular structures (FM – is a ferromagnetic layer or clusters and NM – is non-magnetic spacer or matrix) are of special scientific interest in fundamental research and technological applications. Transition metals or their alloys have been usually employed as FM materials while rare earth have been only occasionally studied as FM components [1-2]. However, one can expect peculiar magnetoresistance behaviour in such materials because the magnetism of rare earth metals depends on 4*f* localized electrons, but conductivity is provided by 5*d* and 6*s* collective electrons [3].

In this work structural features, magnetic properties and magnetoresistance of the Tb/Ti and Tb/Si nanoscale multilayers are comparatively studied.

Experimental

The Tb/Ti and Tb/Si multilayers were prepared by alternative deposition of Tb layers and Ti or Si spacers on glass substrates by rf-sputtering.The base pressure in the chamber was less than 1×10^{-6} mbar and argon gas flow with a pressure of 5×10^{-4} mbar was used during sputtering. The deposition rate was about 0.1 nm/s for Tb and Ti and about 0.03 nm/s for Si. The thickness of the Tb layers in different samples was varied from 1.5 to 6 nm. The thickness of non-magnetic spacers of Ti or Si was kept constant (2 nm). Each sample had protective buffer and coating layers of nonmagnetic material. Magnetoresistance (MR) was measured by a standard four points technique in a longitudinal magnetic field up to 14 T in the temperature range of 2 to 200 K. External magnetic field and current were in plane of the sample. Magnetic properties were measured using a superconducting quantum device (SQUID). The microstructure was examined by X-ray diffraction. Low angle X-ray diffraction was used to determine the quality of the layers in multilayers.

Results and discussion

Fig. 1 shows a low angle x-ray diffractogram for various multilayers. The observed peaks for Tb(6nm)/Ti (a), Tb(3nm)/Si (d) and Tb(1.5nm)/Si (e) are associated with the periodic structure of the multilayers. These peaks allow the determination of the layer thickness, which agrees well with those expected from the deposition time. Set of the maxima disappears for the samples with Ti spacer when the thickness of the Tb is equal to 1.5 nm. The absence of the set of the maxima and sharp decay of the intensity of radiation at $2\Theta < 1°$ indicate that the thickness of the layers is similar

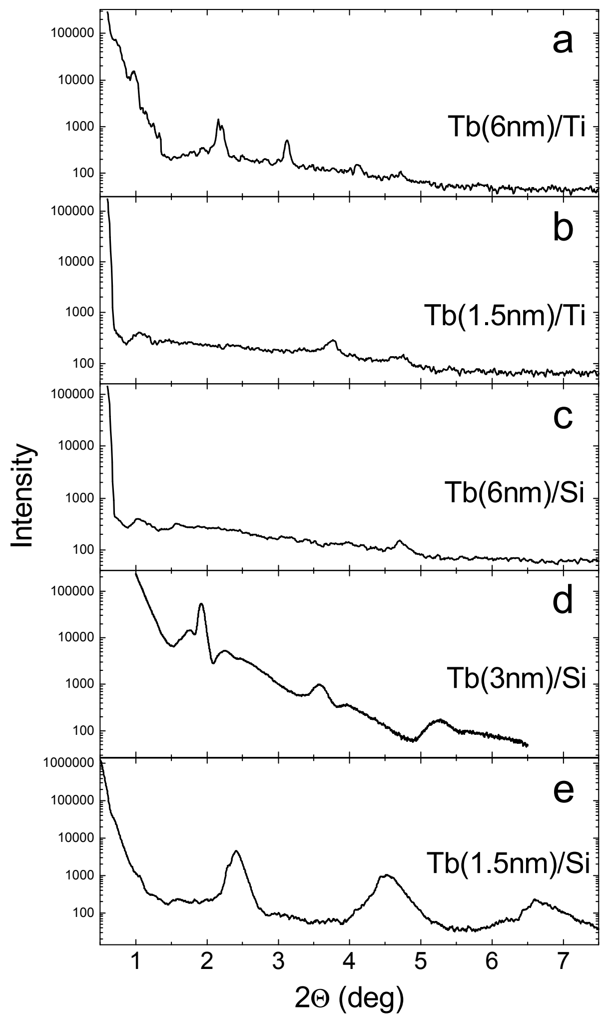

Fig. 1. Low angle x-ray diffractograms for different Tb/Ti and Tb/Si multilayers.

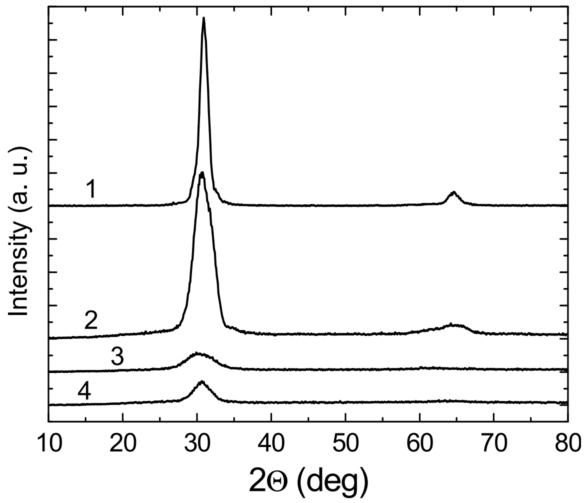

Fig. 2. X-ray diffractograms for $[Tb(6nm)/Ti]_{20}$ (1), $[Tb(3nm)/Ti]_{40}$ (2), $[Tb(1.5nm)/Ti]_{60}$ (3), $[Tb(6nm)/Si]_{20}$ (4) multilayers.

to the roughness of the interfaces. It is possible to expect that $[Tb(1.5nm)/Ti]_{60}$ multilayer contains not continuous Tb layers, but island-like residuals of these layers or that Tb particles are distributed in a Ti matrix, because Ti and Tb are immiscible metals [4]. A different situation was observed for the samples with Si spacers. The shape of the spectrum in Fig. 1(c) leads to a supposition about island-like structure at L_{Tb} = 6 nm. It can be a consequence of much higher roughness of the interfaces of Si containing mutilayers. However diffractograms of the samples with smaller L_{Tb} again show the specific features typical for regular periodic multilayered structure (Fig. 1(d, e)). Recently B. Kjornrattanawanich *et al* [5] have shown, by means of high-resolution TEM for Tb/Si multilayers prepared by rf-sputterring that there is a substantial intermixing at the Tb–Si interfaces: the Tb-Si interlayer has a thickness of approximately 4-5 nm. Therefore it is unlikely that in our case Tb/Si multilayers with L_{Tb} < 5 nm contain island-like residuals of Tb and Si layers, but with high probability their structure consists of rather homogeneous layers of amorphous Tb-Si alloys. The increased layer homogeneity leads again to the appearance of clear peaks on the diffractograms.

Fig. 2 shows selected x-ray spectra for Tb/Ti and Tb/Si structures with different thickness of Tb layers. For all samples the increase of the peaks width was observed with a decrease of the layer thickness. It was also found that the material of the spacers influenced the structure of the rare earth layers. As an example the Tb(6nm)/Ti and Tb(6nm)/Si multilayers can be compared (Fig. 2). For these samples the correlation lengths, d, were calculated using the Scherer's equation $d = 0.9\ \lambda/B\cos\theta_B$, where λ is the radiation wavelength, B is the full width of the x-ray peak at half maximum and θ_B is the position of the peak. For 6 nm Tb layer thickness the correlation length of the Tb/Ti structure was calculated as d = 4 nm and for Tb/Si as d = 3 nm. In the last case the

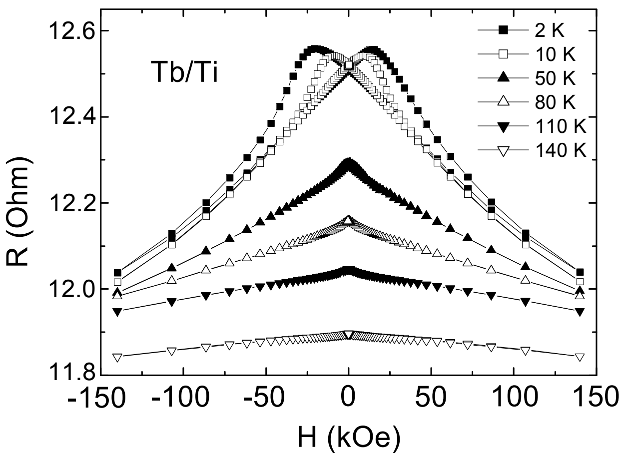

Fig. 3. Magnetoresistance curves of the $[Tb(1.5nm)/Ti]_{60}$ sample at different temperatures.

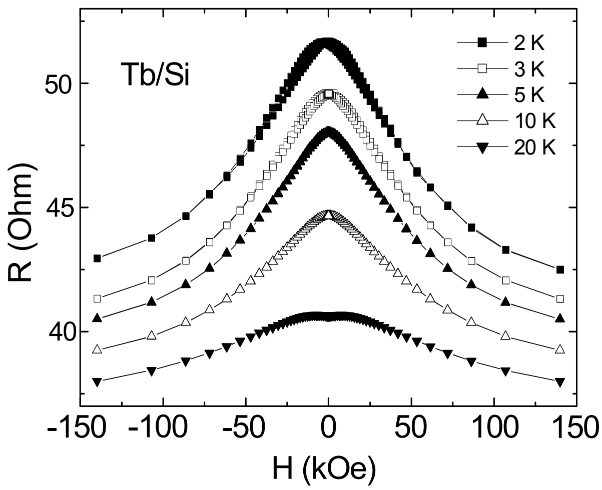

Fig. 4. Magnetoresistance curves of the $[Tb(1.5nm)/Si]_{60}$ sample at different temperatures.

structure appeared to be close to the transition state between nanocrystaline and amorphous like. This peak transforms in clear amorphous halo for Tb(3nm)/Si multilayer. For Tb/Ti the diffraction peak transforms in clear amorphous halo for L_{Tb} = 1.5 nm. For Ti-spacers the multilayers were in the nanostructured state even for the smaller thickness of the Tb layers. As an example Fig. 2 (curve 3) shows the wide x-ray diffraction peak and halo of Tb(1.5 nm)/Ti sample. The co-existence of a peak and halo indicates the presence of two structural phases (nanocrystalline and amorphous) in the sample. It can be pointed out as a summary of the structural studies that the co-existence of granular structure and Tb-Si amorphous alloy is possible for Tb/Si multilayers. Formation of the granular structure can be expected for Tb/Ti multilayers at $L_{Tb} < 1.5$ nm.

The magnetoresistance curves for all investigated multilayers have a similar shape. At low temperature both types of multilayer show large negative magnetoresitance, i.e. the resistance decreases with an increase of the magnetic field *H*. Figs. 3 and 4 show as example MR curves for $[Tb(1.5nm)/Ti]_{60}$ and $[Tb(1.5nm)/Si]_{60}$ samples, respectively. The highest field available (140 kOe) was not enough to achieve complete saturation. Below certain temperature T_0 for all multilayers (both with Ti and Si spacers) a hysteresis of the MR*(H)* magnetoresitive curves was observed. T_0 depends on the thickness of terbium layer and on the type of the material of non-magnetic spacer. For example, $T_0 \approx 130$ K for $[Tb(1.5nm)/Ti]_{60}$ and $T_0 \approx 10$ K for $[Tb(1.5nm)/Si]_{60}$ sample.

Taking into account that longitudinal magnetoresistance is positive for terbium [6] the observed negative MR of Tb/Ti and Tb/Si multilayers can be attributed to the isotropic magnetoresistance or giant magnetic resistance (GMR) if granular structure is present in the samples. The above mentioned structural investigation showed the possibility of granular structure formation for studied multilayers in certain interval of the thickness L_{Tb}. However MR curves of the same type were obtained for all Tb thicknesses and both Si and Ti sublayers indicating that the nature of the observed magnetoresistance effect is an isotropic magnetoresistance (i.e., independent of the angle between the field and the current). The application of an external magnetic field orients the local magnetic moments and therefore leads to a decrease of scattering of conductive electrons, caused by spin disorder.

At low temperatures ΔR/R value, where ΔR/R = [R(H=0)-R(H=140kOe)]/R(H=0), for Tb/Si is significantly higher than MR of Tb/Ti (Fig. 5). In accordance with structural studies Si spacer promotes the Tb amorphisation and as a consequence decrease the crystalline magnetic anisotropy of terbium. The data on the field dependence of the magnetization confirm this supposition (Fig.6). It is seen that the coercivity is much higher for Tb/Ti. Low magnetic anisotropy makes possible to reach the higher level of the ordering of local magnetic moments, therefore decreasing the spin disorder scattering.

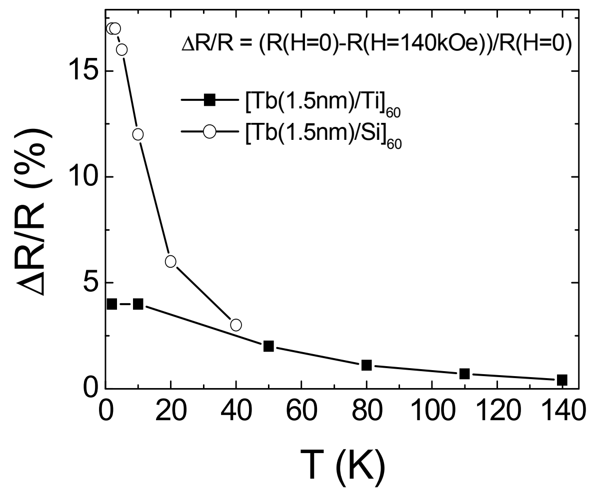

Fig. 5. MR for Tb/Ti (a) and Tb/Si (b) multilayers with L_{Tb} = 1.5 nm.

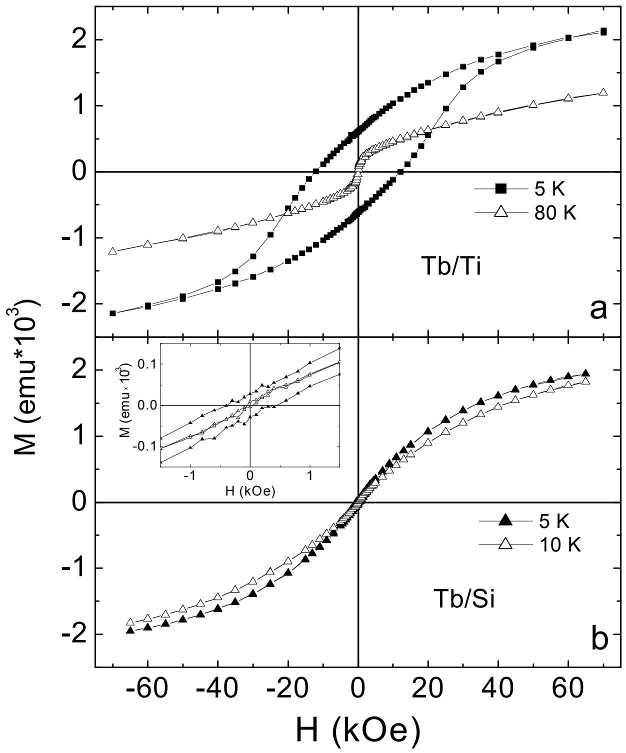

Fig. 6. $M(H)$ curves for Tb/Ti (a) and Tb/Si (b) multilayers with L_{Tb} = 1.5 nm.

Summary

Negative longitudinal magnetoresistance was observed for Tb/Ti and Tb/Si multilayers with various Tb layer thicknesses. The comparative study of the structure, magnetic and magnetoresistive properties leads to a supposition that the nature of the observed negative longitudinal MR can be described as an isotropic magnetoresistance.

Acknowledgment

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